Self-Imaging Nd:YAG waveguide laser with 58% slope efficiency

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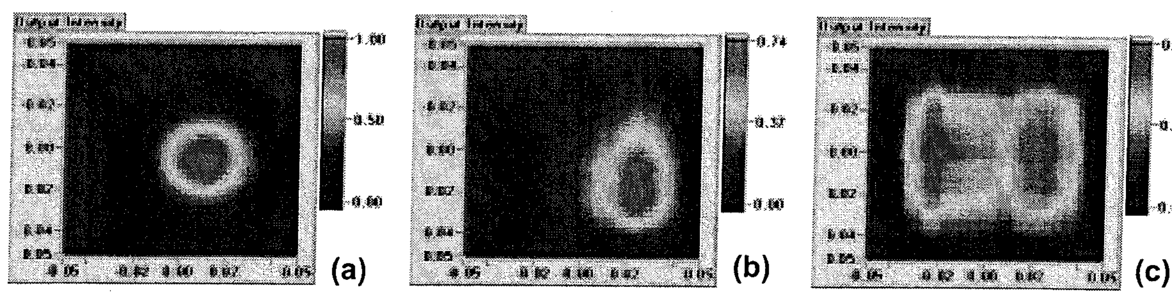
Abstract: We report a novel compact architecture for highly-efficient TEM_{00} solid state lasers. Near diffraction-limited output is demonstrated in a highly-multimode 2-dimensional Nd:YAG waveguide laser with CW and Q-switched slope efficiencies of 58% and 46%, respectively.

OCIS Codes: (110.4190) Multiple imaging ; (140.3300) Laser beam shaping; (140.3530) Lasers, neodymium; (140.3580) Lasers, solid-state

A novel compact waveguide architecture for highly efficient, near-diffraction-limited solid state lasers is demonstrated. High beam quality is obtained in rectangular-aperture *multi-mode* dielectric waveguides by a patent-pending "self-imaging" process[1]. We define self-imaging as the condition that an optical beam will periodically re-image within a multi-mode rectangular waveguide. This behavior was first reported almost 30 years ago[2] and is currently used in telecommunications, but to our knowledge it has not previously been implemented in solid state lasers. The self-imaging waveguide architecture is well-suited to demanding moderate-power-level applications such as deep space communication, and also to power-scaling to >100W powers.

Although high efficiency and diffraction-limited beam quality are routinely obtained in single-mode planar waveguide and fiber lasers, power and energy scaling in these devices is severely restricted by optical damage and parasitic nonlinear effects. Self-imaging enables the efficiency and beam quality of single-mode devices to be retained while scaling the aperture size by a factor of >10000. The self-imaging scheme can be used in one- or two-dimensional geometries. Figure 1 shows modeling of self-imaging for Gaussian beam propagation in a 2-D multi-mode waveguide. The Gaussian profile quickly becomes multi-mode as it propagates, but reconstructs a Gaussian after an imaging period.



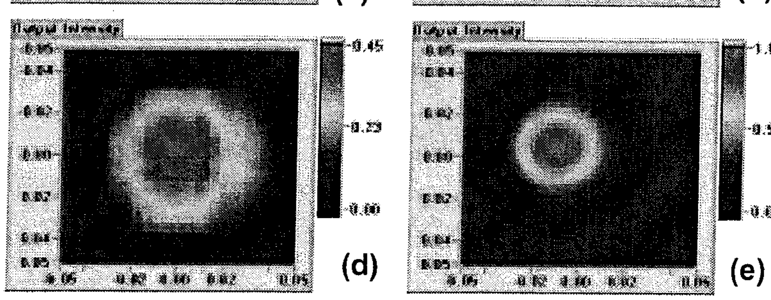
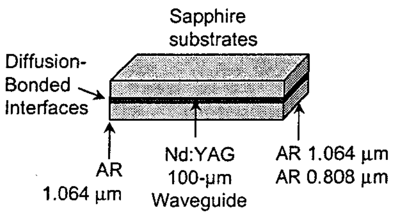


Figure 1. Modeling of self-imaging in a 1-D 100x100μm waveguide. Self-imaging occurs in both directions Starting from top-left, the launched Gaussian beam (a) becomes multi-mode (b-d), then re-images to a Gaussian after one self-imaging length (e).

The self-imaging waveguide architecture has a number of additional attractive features for solid state lasers and amplifiers including: small footprint; thermally robust design; reduced sensitivity to thermal lensing; power scaling to 100W levels in a single waveguide and to kW levels in successive waveguides; energy scaling to ~200mJ/10ns pulses, polarization-preservation and high efficiency through excellent modal overlap and simple close-coupling of diode emitters or bars.

We have developed self-imaging 1 and 2-D Nd:YAG lasers and amplifiers based on 100μm×10mm rectangular aperture waveguides. A thin layer of 0.8% doped Nd:YAG is diffusion-bonded to sapphire cladding layers to give a 1-D waveguide with a numerical aperture of 0.47 (Figure 2). 2-D confinement is provided by additional gain-guiding in the horizontal plane.



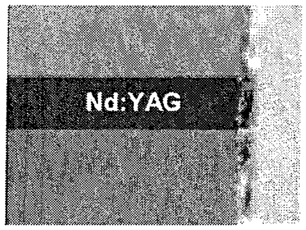


Figure 2. Nd:YAG self-imaging waveguide. LEFT: waveguide design of showing 100μm Nd:YAG layer diffusion-bonded between two sapphire substrates. Right: photograph of Nd:YAG layer between sapphire cladding.

Self-imaging behavior has been confirmed in these waveguides by launching a TEM_{00} 1064nm beam and measuring the waveguide output. A TEM_{00} beam was extracted with no measurable degradation of the $<0.2\lambda$ peak-to-valley input wavefront flatness. Coupling efficiency of diode light into the waveguide was >90%. A CW Nd:YAG 1-D waveguide laser has also been developed, pumped by a single CW diode bar. The resonator used a cylindrical (75% reflectance) output coupler to define a TEM_{00} mode in the confined waveguide dimension. A maximum output power of 16W was obtained with 39% slope efficiency. M^2 was <1.5 in the guided direction, with a multimode output in the unconfined direction.

Near-diffraction-limited output in both directions at moderate power levels has been obtained by a combination of index and gain-guiding in a 2-D self-imaging waveguide, as described above. In this case, the waveguide laser is pumped by a close-coupled 808nm single-emitter diode. Figure 3 summarizes the 2-D waveguide laser configuration and performance. A CW slope efficiency of 58% was measured with respect to absorbed pump power, corresponding to a 1064nm output of 1.5W at 4.3W diode power. The output beam was close to diffraction-limited with M^2 of 1.0 and 1.5 in the gain-guided and index-guided directions, respectively. For pulsed operation at 10-100kHz an acousto-optic Q-switch was inserted in the cavity. The maximum pulsed laser efficiency was 42% with respect to pump diode power.

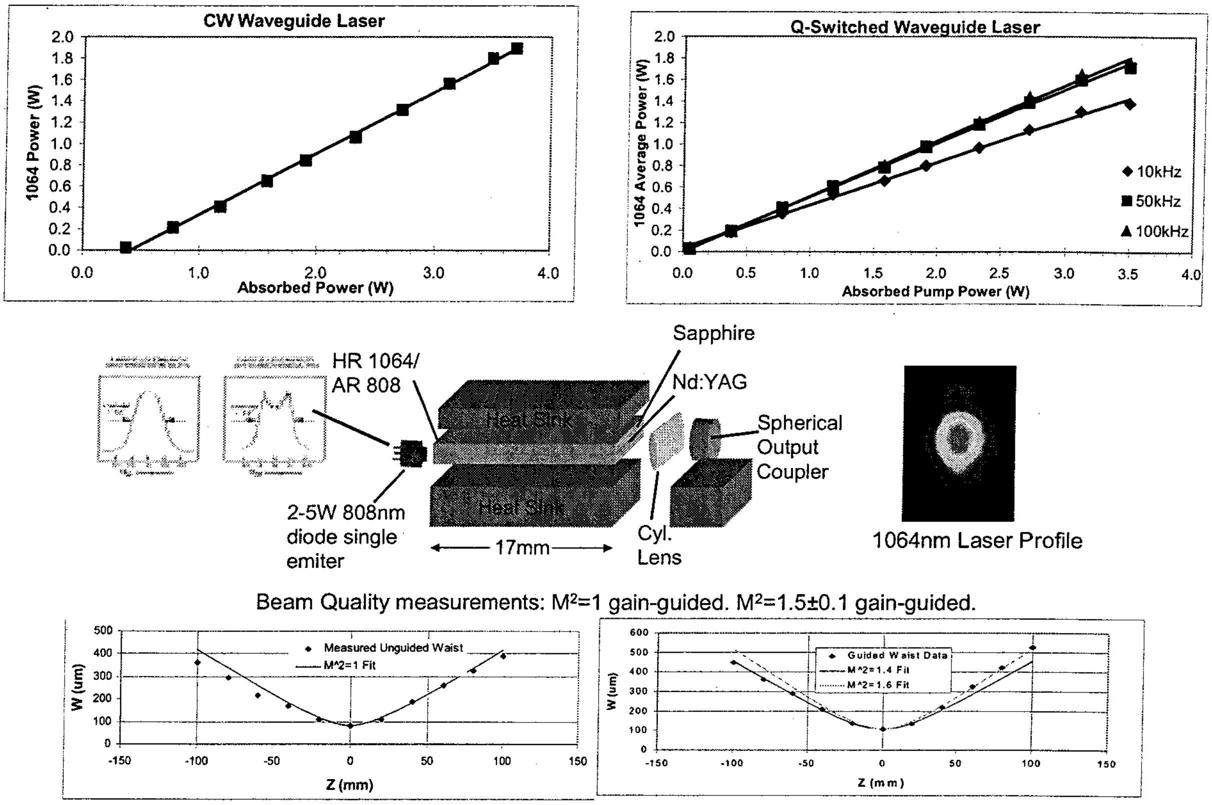


Figure 3. 2-D Nd:YAG waveguide laser. *Upper left* - CW laser efficiency. *Upper Right* – Q-switched laser efficiency as a function of absorbed pump power. Pump absorption was ~ 90%. *Center* - schematic of 2-D CW waveguide laser with measured 1064nm spatial beam profile. Fast axis pump light is collected and index-guided in the waveguide. Slow axis pump divergence provides gentle gain-guiding for the Nd:YAG laser mode. The resonator is astigmatic with a waist in the gain-guided direction at the waveguide back (left) face and a waist in the index-guided direction at the waveguide entrance (right) face. For pulsed operation, a Q-switch is inserted between the cylindrical lens and the output coupler. *Lower* – M^2 measurements for the gain-guided (left) and index-guided (right) directions, showing measured beam spotsize with propagation distance, and fitted curves.

[1] L. Soldano et al J. Lightwave Tech. **13**, 615 (April 1995); and references therein.
[2] O. Bryngdahl, J. Opt. Soc. Am. **63**, 416 (1973); R. Ulrich and G. Ankele, Appl. Phys. Lett. **27**, 337 (1975).